Two Stages Active Disturbance Rejection Control for Coupled Permanent Magnet Synchronous Motors System with Mismatch Disturbance

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Two Stages Active Disturbance Rejection Control for Coupled Permanent Magnet Synchronous Motors System with Mismatch Disturbance

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Abstract Aiming at the disturbance mismatch in the coupled permanent magnet synchronous motors (CPMSMs) system, a new design method of active disturbance rejection controller (ADRC) is proposed in this paper. In order to eliminate the coupling tension between motors, the control law is designed in two stages, so that the disturbance and control input appear in the same channel, and then the ADRC is designed to realize the control goal by using the control input. The proposed method is more universal than the previous methods, and the parameter tuning is easier. At the same time, it simplifies the design steps of the controller and reduces the requirements of the control system.

Keywords ADRC · CPMSMs · synchronous control · mismatch disturbance

1 Introduction

Compared with the traditional electrically excited synchronous motor, permanent magnet synchronous motor (PMSM) has the advantages of simple structure, reliable operation, small volume, light weight, low loss, high efficiency, flexible and diverse motor shape and size. In recent years, with the continuous development of material technology, the continuous improvement of the performance of permanent magnet materials and the continuous maturity of permanent magnet motor control technology, PMSM has been widely used in civil, aerospace, military and other fields. However, PMSM is a complex object with multivariable, strong coupling, nonlinearity and variable parameters. In order to obtain better control performance, it is necessary to adopt a certain control algorithm [2].

In today’s life, there are a large number of scenes where multi permanent magnet synchronous motors (such as coupled permanent magnet synchronous motors) are used, such as cement cellars, belt conveyors and paper machines. The synchronous performance of the motor will directly affect the quality and efficiency of industrial production, so it is very necessary to strengthen the synchronous performance and anti-interference performance of CPMSMs under the condition of ensuring the stability of the system. The primary purpose of CPMSMs control system is to eliminate synchronization error and realize zero steady-state error. J. Sun et al adopts sliding mode control [13]. In addition to the chattering problem, sliding mode control also needs to consider the speed, inertia, acceleration section and other problems when it is close to the sliding mode surface, and the switching function has a dead zone. After the sliding mode trajectory enters the dead zone, the motion trajectory is uncontrollable. F.-J. Lin et al adopts the combination of fuzzy control and synovial control [12], but the fuzzy inference rule and the number of inputs and outputs may be limited by hardware, and the design of fuzzy control is not systematic and can not define the control target. H. Xiong et al proposed a robust adaptive observer for two PMSMs [14], which can compensate the error of the actuator.

ADRC technology is a control strategy proposed by researcher Han Jingqing in 1998 [7]. It inherits PID’s idea of eliminating errors based on errors, reduces the
internal disturbance and external winding of the system to total disturbance, and takes it as an expanded one-dimensional state, so as to form an expanded state observer [5]. At first, the form of ADRC is nonlinear, and there are many parameters suppose to be adjusted, so it is very difficult to realize the coordination between parameters. Therefore, Gao Zhiquiang proposed a linear active disturbance rejection controller (LADRC), which reduced the original parameters to be adjusted to five, and then proposed the bandwidth method [3], which further reduced the adjusted parameters to one, that is the bandwidth $w_c$ of the controller. The previous literatures almost all discussed the control of single PMSM [9, 10], and rarely discussed the control of two PMSMs, because the coupling effect between two motors should be considered at this time. In addition, some scholars use interval matrix to control CPMSMs system [6], but the effect of its controller may not meet the control requirements.

The original ADRC is designed for the strict integral series system [8], and there is nothing to do for the system that does not meet the integral series form. Subsequently, scholars studied the method of transforming the general model into the integral series form [4]. In addition, when the disturbance and control input are not in the same channel, the original extended state observer is not applicable. Therefore, some scholars proposed a generalized extended state observer [11]. However, it has strict requirements for system matrix, and it is not easy to select parameters.

Therefore, an idea of constructing ADRC in two stages is proposed in this paper. In the first stage, we regard the state variable of the channel where the control input is located as the input of the state variable of the channel where the disturbance is located. Then, we can get the form of the state variable of the channel where the control input is located, which is the form it should have; In the second stage, the form of the state variables of the channel where the control inputs are located are brought into their own state equation, and the control inputs and disturbance are placed in the same channel, so that the form of the control input can be obtained. The next step is the same as the design of conventional LADRC. The block diagram of the whole control system is shown in Figure 1.

The main contributions of this paper are as follows:
(1) Linear ADRC is applied to CPMSMs system;
(2) A two-step design method of ADRC is proposed to overcome the disturbance mismatch.

The structure of this paper is as follows: in Section 2, the mathematical model of CPMSMs is established; In Section 3, the design steps of two-step ADRC are described; In Section 4. The simulation results are given and compared with the previous methods; The conclusion is given in Section 5.

2 Mathematical model of CPMSMs

The mathematical model of single PMSM is

\[
\begin{align*}
\frac{di_d}{dt} &= -\frac{R_s}{L_{sd}} i_d + \frac{L_{sq}}{L_{sd}} \omega i_q + \frac{1}{L_{sd}} u_d \\
\frac{di_q}{dt} &= -\frac{L_{sq}}{L_{sd}} \omega i_d - \frac{R_s}{L_{sq}} i_q - \frac{1}{L_{sq}} \omega \psi_r + \frac{1}{L_{sq}} u_q \\
\frac{d\omega}{dt} &= \frac{n^2}{J} (L_{sd} - L_{sq}) i_d i_q + \frac{n^2}{J} \psi_r i_q - \frac{n^2}{J} T_l - \frac{B}{J}\omega
\end{align*}
\]

Where $i_d$—d-axis stator current; $i_q$—q-axis stator current; $\omega$—rator speed; $R_s$—stator resistance; $L_{sd}$—d-axis inductance; $L_{sq}$—q-axis inductance; $\psi_r$—permanent magnet flux linkage; $J$—inertia moment; $u_d$—d-axis voltage; $u_q$—q-axis voltage; $T_l$—load torque; $B$—Frictional coefficient of motor.
According to the control block diagram and [6], the model of CPMSMs is constructed as follows:

$$\frac{di_d}{dt} = \frac{R_{s1}}{L_{sd1}}i_{q1} - \frac{L_{sq1}}{L_{sd1}}\omega_1i_{q1} + \frac{1}{L_{sd1}}u_{d1}$$

$$\frac{di_q}{dt} = -\frac{L_{sq1}}{L_{sd1}}i_{d1} - \frac{R_{s1}}{L_{sq1}}i_{d1} - \frac{1}{L_{sq1}}\omega_1i_{d1} + \frac{1}{L_{sq1}}u_{q1}$$

$$\frac{d\omega_1}{dt} = n_{p1}^q(L_{sd1} - L_{sq1})i_{d1}i_{q1} + \frac{n_{q1}^2}{J_1}\psi_{r1}i_{q1} - \frac{n_{p1}^2}{J_1}T_{11} - f(t)$$

$$\frac{d\omega_2}{dt} = B_2\frac{1}{J_2}\omega_2 + f(t)$$

(2)

Remark 1. $f(t)$ represents the coupling tension between motors, $T_{11}$ and $T_{12}$ are load torques. Subscripts 1 and 2 in formula (2) represent the parameters of No. 1 motor and No. 2 motor respectively.

It is not difficult to find that the d-axis and q-axis of the motor are coupled at this time. In order to realize the static decoupling of the d-axis and q-axis currents, we adopt the control of id = 0 (i.e., $i_{d1}$ and $i_{d2}$ are equal to zero), and the model of CPMSMs is further simplified as:

$$\frac{di_{d1}}{dt} = \frac{R_{s1}}{L_{sd1}}i_{q1} - \frac{L_{sq1}}{L_{sd1}}\omega_1i_{q1} + \frac{1}{L_{sd1}}u_{d1}$$

$$\frac{di_{d2}}{dt} = -\frac{L_{sq2}}{L_{sd2}}i_{d2} - \frac{R_{s2}}{L_{sq2}}i_{d2} - \frac{1}{L_{sq2}}\omega_2i_{d2} + \frac{1}{L_{sq2}}u_{d2}$$

$$\frac{d\omega_1}{dt} = n_{p1}^q(L_{sd1} - L_{sq1})i_{d1}i_{q1} + \frac{n_{q1}^2}{J_1}\psi_{r1}i_{q1} - \frac{n_{p1}^2}{J_1}T_{11} - f(t)$$

$$\frac{d\omega_2}{dt} = \frac{n_{p2}^q}{J_2}\psi_{r2}i_{q2} - \frac{n_{q2}^2}{J_2}\psi_{r2}i_{q2} - \frac{n_{p2}^2}{J_2}T_{12} + f(t)$$

(3)

We can see that the control input of the motor is $u_{d1}, u_{q1}$ and disturbance $f(t)$ are not in the same channel, which is called disturbance mismatch. At this time, conventional ADRC cannot be designed for control. We need to find a way to place the control input and disturbance in the same channel, which is what we will do in the next section.

3 Design of two-step ADRC

3.1 The first stage of design

The generalized extended state observer has some disadvantages, such as strict requirements for system matrix and difficult selection of parameters. Here we propose a two-step ADRC design method. Firstly, we first extract the speed equation in system (3) as the control objective of the first step, that is:

$$\frac{d\omega_1}{dt} = n_{p1}^q\psi_{r1}i_{q1} - \frac{B_1}{J_1}\omega_1 - \frac{n_{p1}^2}{J_1}T_{11} - f(t)$$

$$\frac{d\omega_2}{dt} = n_{p2}^q\psi_{r2}i_{q2} - \frac{B_2}{J_2}\omega_2 - \frac{n_{p2}^2}{J_2}T_{12} + f(t)$$

(4)

We write it as a state space equation as follows

$$\begin{pmatrix}
\dot{\omega}_1 \\
\dot{\omega}_2 \\
\end{pmatrix} =
\begin{pmatrix}
a_1 & 0 \\
0 & a_2 \\
\end{pmatrix}
\begin{pmatrix}
\omega_1 \\
\omega_2 \\
\end{pmatrix} + 
\begin{pmatrix}
b_1 & 0 \\
0 & b_2 \\
\end{pmatrix}
\begin{pmatrix}
i_{q1} \\
i_{q2} \\
\end{pmatrix} + 
\begin{pmatrix}
-1 & 0 \\
0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
f(t) \\
f(t) \\
\end{pmatrix}$$

(5)

Where $a_3 = -\frac{\omega_1}{J_1}, a_2 = -\frac{\omega_2}{J_2}, b_1 = \frac{n_{p1}^\varphi_1}{J_1}, b_2 = \frac{n_{p2}^\varphi_2}{J_2}, g_1 = -\frac{n_{p1}^2}{J_1}, g_2 = -\frac{n_{p2}^2}{J_2}$.

Define matrixes $A_1 = \begin{pmatrix} a_1 & 0 \\ 0 & a_2 \end{pmatrix}$; $B_1 = \begin{pmatrix} b_1 & 0 \\ 0 & b_2 \end{pmatrix}$; $F_1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$; $G_1 = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \end{pmatrix}$.

Taking the current $i_{q1}$ and $i_{q2}$ as its control inputs, we can get the form (6) that $i_{q1}$ and $i_{q2}$ should have in order to eliminate the total disturbance $f(t)$, i.e.

$$\begin{pmatrix}
i_{q1} \\
i_{q2} \\
\end{pmatrix} =
\begin{pmatrix}
-1 & f(t) + k_{11}(w_{1rcf} - w_1) + k_{12}(w_{2rcf} - w_2) \\
-1 & f(t) + k_{21}(w_{1rcf} - w_1) + k_{22}(w_{2rcf} - w_2) \\
\end{pmatrix}
\begin{pmatrix}
\frac{1}{b_1}T_{11} \\
\frac{1}{b_2}T_{12} \\
\end{pmatrix}$$

(6)

$$K_1 = \begin{pmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{pmatrix}$$ is the gain of the first controller, which can be obtained by pole assignment of (5), and then enter the second stage of design.

Assumption 1. The total disturbance $f(t)$ is second-order differentiable. That is, $f(t) = h_1(t), h_2(t) = h_2(t)$. The load torque $T_{11}$ and $T_{12}$ are constants, i.e. $\dot{T}_{11} = \dot{T}_{12} = 0$. 
3.2 The second stage of design

In the first instance, we substitute equation (6) and the derivative of (6) into the system of the channel where the control inputs \(u_q1\) and \(u_q2\) are located, that is, the system shown in equation (7)

\[
\begin{pmatrix}
\dot{i}_{q1} \\
\dot{i}_{q2}
\end{pmatrix} = \begin{pmatrix}
a_3 & 0 \\
0 & a_4
\end{pmatrix} \begin{pmatrix}
i_{q1} \\
i_{q2}
\end{pmatrix} + \begin{pmatrix}
b_0 & 0 \\
0 & b_3
\end{pmatrix} \begin{pmatrix}
w_1 \\
w_2
\end{pmatrix} + \begin{pmatrix}
c_1 & 0 \\
0 & c_2
\end{pmatrix} \begin{pmatrix}
u_q1 \\
u_q2
\end{pmatrix}
\]

(7)

Where \(a_3 = -\frac{R_{c1}c_k2}{L_{c2}}\); \(a_4 = -\frac{R_{c2}c_k2}{L_{c2}}\); \(b_3 = -\frac{c_k1}{L_{c2}}\); \(c_1 = \frac{c_k1}{L_{c2}}\); \(c_2 = \frac{1}{L_{c2}}\).

Then the controlled object is

\[
\begin{pmatrix}
\dot{w}_1 \\
\dot{w}_2
\end{pmatrix} = \begin{pmatrix}
a_3 - \frac{b_0}{k_{11}} & 0 \\
0 & a_4 - \frac{b_0}{k_{22}}
\end{pmatrix} \begin{pmatrix}
w_1 \\
w_2
\end{pmatrix} + \begin{pmatrix}
c_1 & 0 \\
0 & c_2
\end{pmatrix} \begin{pmatrix}
u_q1 \\
u_q2
\end{pmatrix} + \begin{pmatrix}
-\frac{a_3}{k_{11}^2} & 0 \\
0 & -a_4
\end{pmatrix} \begin{pmatrix}
w_{1ref} \\
w_{2ref}
\end{pmatrix} + \begin{pmatrix}
\frac{a_3}{k_{11}^2}b_1 & 0 \\
0 & \frac{a_4}{k_{22}^2}b_2
\end{pmatrix} \begin{pmatrix}
T_{11} \\
T_{12}
\end{pmatrix}
\]

(8)

Define matrices:

\[
A_2 = \begin{pmatrix}
a_3 - \frac{b_0}{k_{11}} & 0 \\
0 & a_4 - \frac{b_0}{k_{22}}
\end{pmatrix}; \\
B_2 = \begin{pmatrix}
c_1 & 0 \\
0 & c_2
\end{pmatrix}; \\
R = \begin{pmatrix}
-\frac{a_3}{k_{11}^2} & 0 \\
0 & -a_4
\end{pmatrix}; \\
G_2 = \begin{pmatrix}
\frac{a_3}{k_{11}^2}b_1 & 0 \\
0 & \frac{a_4}{k_{22}^2}b_2
\end{pmatrix}
\]

The next design idea is the same as the conventional ADRC design. At first, we need to construct the expansion system (9) of (8). If we take the total disturbance \(f(t)\) and its derivative \(h_1\) as the extended two-dimensional state variable, and define their second derivative is \(h_2\), there is

\[
\begin{pmatrix}
\dot{w}_1 \\
\dot{w}_2 \\
\dot{f}(t) \\
\dot{h}_1
\end{pmatrix} = \begin{pmatrix}
\dot{w}_1 \\
\dot{w}_2 \\
\dot{f}(t) \\
\dot{h}_1
\end{pmatrix} = A_L \begin{pmatrix}
w_1 \\
w_2 \\
f(t) \\
h_1
\end{pmatrix} + B_L \begin{pmatrix}
u_q1 \\
u_q2
\end{pmatrix} + R_L \begin{pmatrix}
w_{1ref} \\
w_{2ref}
\end{pmatrix} + G_L \begin{pmatrix}
T_{11} \\
T_{12}
\end{pmatrix} + F_L * h_2
\]

(9)

Define matrix

\[
A_L = \begin{pmatrix}
a_3 - \frac{b_0}{k_{11}} & 0 & -\frac{a_3}{k_{11}^2} & -1 \\
0 & a_4 - \frac{b_0}{k_{22}} & -\frac{a_4}{k_{22}^2} & 0 \\
0 & 0 & \frac{c_1}{k_{11}} & 0 \\
0 & 0 & 0 & \frac{c_2}{k_{22}}
\end{pmatrix}
\]

(10)

\[
B_L = \begin{pmatrix}
\frac{c_1}{k_{11}} & 0 \\
0 & \frac{c_2}{k_{22}}
\end{pmatrix}; \\
R_L = \begin{pmatrix}
0 & a_3 \\
0 & 0
\end{pmatrix}; \\
F_L = \begin{pmatrix}
0 \\
0
\end{pmatrix};
\]

(11)

\[
G_L = \begin{pmatrix}
0 & \frac{a_3}{k_{11}^2} & 0 \\
0 & 0 & 0
\end{pmatrix}; \\
C_L = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{pmatrix}
\]

Further, we can obtain that the extended state observer is

\[
\begin{pmatrix}
\dot{w}_1 \\
\dot{w}_2 \\
\dot{f}(t) \\
\dot{h}_1
\end{pmatrix} = A_L \begin{pmatrix}
w_1 \\
w_2 \\
f(t) \\
h_1
\end{pmatrix} + B_L \begin{pmatrix}
u_q1 \\
u_q2
\end{pmatrix} + R_L \begin{pmatrix}
w_{1ref} \\
w_{2ref}
\end{pmatrix} + G_L \begin{pmatrix}
T_{11} \\
T_{12}
\end{pmatrix} + F_L * h_2
\]

(12)

Where \(\hat{e}\) means the estimated value of \((*)\). Define matrix

\[
\hat{e} = \hat{A} \hat{e} - L \begin{pmatrix}
ev_1 \\
ev_2
\end{pmatrix} - F_L * h_2
\]

(13)

Define the error signal \(e = \hat{x} - x\), then subtract (9) from (11) to obtain the error system as (12)

\[
h_1 = \hat{A} - L * C_L e - F_L * h_2
\]

In order to eliminate the total disturbance, the control inputs \(u_q1\) and \(u_q2\) are designed as shown in (13)

\[
\begin{pmatrix}
u_q1 \\
u_q2
\end{pmatrix} = \begin{pmatrix}
k_{11} & -\frac{a_3}{b_1k_{11}} & \frac{1}{b_1k_{11}} & k_{31}(w_{1ref} - \hat{w}_1) \\
k_{22} & -\frac{a_3}{b_2k_{22}} & \frac{1}{b_2k_{22}} & k_{41}(w_{1ref} - \hat{w}_1)
\end{pmatrix}
\]

(14)

\[
\begin{pmatrix}
u_q1 \\
u_q2
\end{pmatrix} = \begin{pmatrix}
k_{11} & -\frac{a_3}{b_1k_{11}} & \frac{1}{b_1k_{11}} & k_{31}(w_{1ref} - \hat{w}_1) \\
k_{22} & -\frac{a_3}{b_2k_{22}} & \frac{1}{b_2k_{22}} & k_{41}(w_{1ref} - \hat{w}_1)
\end{pmatrix}
\]

(15)

Define matrix \(K_2 = \begin{pmatrix}
k_{31} & k_{32} \\
k_{41} & k_{42}
\end{pmatrix}\) is second controller’s gain matrix.
Table 1 Motors parameters

<table>
<thead>
<tr>
<th>PM motor serial number</th>
<th>NO.1 PM motor</th>
<th>NO.2 PM motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>q-axis inductance(Lq,H)</td>
<td>0.00101</td>
<td>0.00207</td>
</tr>
<tr>
<td>d-axis inductance(Ld,H)</td>
<td>0.00101</td>
<td>0.00207</td>
</tr>
<tr>
<td>stator resistance(Rs,Ω)</td>
<td>0.24</td>
<td>0.62</td>
</tr>
<tr>
<td>rotor flux(φr,wb)</td>
<td>0.06781</td>
<td>0.08627</td>
</tr>
<tr>
<td>pole pairs(np)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>friction coefficient(Z,Nm/rad/s)</td>
<td>0.0001619</td>
<td>0.00009444</td>
</tr>
<tr>
<td>moment inertia(l,kg/m²)</td>
<td>0.00048</td>
<td>0.003617</td>
</tr>
</tbody>
</table>

Bring (13) into the original system (8) and combine (12) to form a closed-loop system (14).

\[
\begin{pmatrix}
\dot{w}_1 \\
\dot{w}_2 \\
\dot{e}_w_1 \\
\dot{e}_w_2 \\
\dot{e}_h_1 \\
\end{pmatrix} =
\begin{pmatrix}
A_2 - B_2 K_2 & (-B_2 * K_2, -F_2) \\
0 & A_L - L * C_L \\
R - B_2 * K_2 & 0_{4 \times 2} \\
0_{4 \times 2} & 0_{2 \times 2}
\end{pmatrix}
\begin{pmatrix}
w_1 \\
w_2 \\
e_{w_1} \\
e_{w_2} \\
e_{h_1}
\end{pmatrix}
+ \begin{pmatrix}
G_2 \\
0_{4 \times 2}
\end{pmatrix}
\begin{pmatrix}
T_{11} \\
T_{12} - 0_{2 \times 2} \\
F_L 
\end{pmatrix}
h_2
\]  

Finally, we need to assign the poles of \((A_2 - B_2 * K_2)\) to get the parameters of the second controller. The parameters of the observer are obtained by pole assignment of \((A_L - L * C_L)\). So far, the whole two-step process of designing ADRC is completed. Throughout the whole design process, our design steps are very simple and clear, which is easier to be applied in practical projects than the methods in other references. In the next section, we will give the results of numerical simulation.

4 Numerical simulation

The simulation in this section shows the effectiveness of the proposed method. We adopt the same motor parameters as [1], as shown in Table 1. In addition, the load torque \(T_{11} = 1.5 \text{Nm}, T_{12} = 1 \text{Nm}\).

The gain of the first controller can be obtained by pole assignment of the first stage system, and the assigned poles are \(-1.9118e4\) and \(-1.1307e4\), so \(K_1 = \begin{pmatrix} 5 & 0 \\ 0 & 5 \end{pmatrix}\).

Then, the system in the second stage is obtained, and its poles are allocated. The allocated poles are \(-2.8029e+6\) and \(-2.3551e+6\), and the gain K2 of the second controller is obtained; The poles of the error system are \(-1243.03, -1375.2, -0.000186 + 0.0143i\) and \(-0.000186 - 0.0143i\), and the observer gain L is obtained.

\[
K_2 = \begin{pmatrix} 189.6237 & -4.3874 \\ 20.9644 & 187.9570 \end{pmatrix}, L = \begin{pmatrix} -10 & 7 \\ -10 & 12 \\ -0.21 & 0.07 \\ -0.72 & -0.5 \end{pmatrix}.
\]

4.1 Synchronization performance

As in reference [1], we set the given speed to 90. The simulation results are shown in Figure 2 and figure 3. \(w_1\) and \(w_2\) are synchronized almost instantaneously. Although their initial synchronization error is relatively large, reaching 19.41, it will soon be reduced to almost zero. Obviously, our effect is better than that in reference [1], our response is faster and the adjustment time is shorter.

4.2 Disturbance rejection performance

4.2.1 Given value mutation

We change the given value to 70 at 0.05s, and the output of the system is shown in Figure 4 and 5. It can be seen that \(w_1\) is stable after 0.002s and \(w_2\) is stable after 0.003s. It can be seen that the designed ADRC can respond quickly to the given change.
4.2.2 Disturbance mutation

Sinusoidal disturbance On the basis of subsection 4.1, we add the disturbance \( f = 30\sin(100\pi t) \) in 0.05s, as we can see in Figure 6 and 7, the rotating speeds \( w_1 \) and \( w_2 \) return to stability after 0.005s and remain synchronized. The synchronization error between rotating speeds is affected by disturbance and returns to stability after 0.005s. From the control signals \( u_{q1} \) and \( u_{q2} \), they react immediately after the disturbance mutation and reach a new balance after 0.006s, so that the synchronization performance of the system is not affected.

Remark 2. Before the addition of \( f \), the system has included the initial disturbance \( 50\sin(100\pi t) \). Because the disturbance is in the form of trigonometric function, that is, the disturbance is changing all the time, so each signal fluctuates within a certain amplitude, but the fluctuation range is completely within the acceptable range. After adding the new disturbance \( f \), the system can respond quickly, so that the speed can still track the given speed, and the error remains almost zero.

Constant disturbance The derivative trigonometric function disturbance is considered above, but the constant step disturbance is common in engineering practice. This section will test the step disturbance. The initial disturbance is \( f = 2000 \), and the step disturbance of 2000 is added at 0.05s. At this time, the derivative of the disturbance is a pulse signal. In order to avoid the system collapse caused by its infinity and combined with the physical performance of the actual device, it is necessary to limit the amplitude of the control input signals \( u_{q1} \) and \( u_{q2} \) (the amplitude limit in this paper is \([-1200, 1200]\), and the amplitude of the pulse signal is set to \( 1e10 \)). The simulation results are shown in Figure 9 and 10. It can be seen that the disturbance has little effect on W1, and the overshoot of W2 is 26, but both of them return to stability after 0.001s. Therefore, the controller can also suppress the step disturbance.

Remark 3. Note that at this time, the parameters need to be adjusted. The poles of No. 1 controller are placed at \(-2.2613e5 \) and \(-0.7647e5 \), the poles of No. 2
controller are placed at \(-2.8029e6\) and \(-2.3551e6\), and the poles of leso are placed at \(-1.012e5, -5.1364e4, -0.0341 + 0.1711i\) and \(-0.0341 - 0.1711i\). The parameter matrix

\[
K_1 = \begin{pmatrix} 100 & 0 \\ 0 & 20 \end{pmatrix}; \quad K_2 = \begin{pmatrix} 189.6237 & -4.3874 \\ 20.9644 & 187.957 \end{pmatrix}; \quad L = \begin{pmatrix} 1e5 & -10 \\ 3 & 5e4 \\ -2.4e3 & 780 \\ -700 & 500 \end{pmatrix}.
\]

In addition, the parameters at this time can fully ensure other performance of the system (i.e. tracking, anti-interference and synchronization performance mentioned in the context), but the adjustment time is relatively slow, but it can also ensure stability within a few milliseconds, as shown in the appendix).

\[
\begin{align*}
0 & 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.1 \\
0.048 0.05 0.052 0.054 0.056 & 0.058 0.06 0.062 0.064 0.066 \\
-0.08 & -0.06 -0.04 -0.02 0 & 0.02 0.04 0.06 0.08 0.1 \\
-0.08 & -0.06 -0.04 -0.02 0 & 0.02 0.04 0.06 0.08 0.1 \\
\end{align*}
\]

4.3 Tracking performance

In the tracking performance test, we set the given speed to \(70\sin(100\pi t)\). As can be seen from Figure 9, at this time, the system can still track the given speed and realize the synchronization of speed.

Similarly, we add the disturbance \(f = 30\sin(100\pi t)\) in 0.05s (the initial disturbance is \(f = 50\sin(100\pi t)\)). As can be seen from Figure 10, the synchronization error returns to stable after 0.002s. As can be seen from Figure 11, the control signals \(u_{q1}\) and \(u_{q2}\) also respond immediately at 0.005s and return to stability after 0.002s, so that the speed can perfectly track the given speed. Note that the parameters at this time can fully ensure other performance of the system (i.e. tracking, anti-interference and synchronization performance mentioned in the context), but the adjustment time is relatively slow, but it can also ensure stability within a few milliseconds, as shown in the appendix).

\[
\begin{align*}
0 & 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.1 \\
0.048 0.05 0.052 0.054 0.056 & 0.058 0.06 0.062 0.064 0.066 \\
-0.08 & -0.06 -0.04 -0.02 0 & 0.02 0.04 0.06 0.08 0.1 \\
-0.08 & -0.06 -0.04 -0.02 0 & 0.02 0.04 0.06 0.08 0.1 \\
\end{align*}
\]

5 Conclusion

This paper presents a two-stage design method of ADRC. Different from the design of ADRC for disturbance mismatch in previous literature, the proposed method is not in one step, but intercepts the original controlled object into two parts, that is, the part containing disturbance and the part containing control input, and configures the disturbance and input into the same channel by sections. Compared with the previous methods, it has more universality, less high requirements for the system, and greatly enhances the robustness of the system. The requirements for the ra-
pidity of the motion control system can be greatly met. Taking CPMSMs system as an example, the controller design and simulation verification are carried out. The simulation results show that the proposed method is effective and its performance is better than the previous methods. In the future, we can extend this idea to more general models, not just in CPMSMs system.

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References

Appendix

From Fig.14 and Fig.15, we can see that the adjustment time is 4.67\,ms and 3\,ms respectively.

As can be seen from Fig.16 and Fig.17, the adjustment time is 1.39\,ms and 0.79\,ms respectively.

As can be seen from Fig.20 and Fig.21, the system almost instantly returns to stability at 0.05\,s.